AMSE JOURNALS-AMSE IIETA publication-2017-Series: Modelling C; Vol. 78; N°1; pp 83-99
Submitted Jan. 2017; Revised March 15, 2017, Accepted April 15, 2017

Evaluation of Groundwater Function in Tianjin based on Dissipation Theory

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Abstract

Groundwater possesses resources function, ecology function and geological environment function. The eco-environmental and geological problems caused by the unreasonable abstraction of groundwater can all be attributed to the degeneration and loss of groundwater function. The evaluation of groundwater function is the foundation of groundwater management. Groundwater system is dissipative structure system. On the basis of order degree and entropy of dissipative structure system, this paper establish a set of new and more adaptive evaluation index system and evaluation model of groundwater function, which are applied in the evaluation of groundwater function in Tianjin. The results indicate that the region with moderately strong groundwater comprehensive function mainly locates in Ji County. While groundwater comprehensive function in Baodi District and Wuqing District is moderate, and other regions are moderately weak or weak. These findings may help decision-makers for devising sustainable groundwater management strategies in Tianjin.

Key words

Dissipative structure, groundwater function, order parameter, entropy

1. Introduction

Groundwater is the main water source of production, living and ecological water, which bears vital resources, ecology and geological environment function. Groundwater plays an important role in economic and social development, health of ecosystem and stability of geological environment. However, climatic change and human activities exert a significant impact on groundwater system and destroy the evolution law of groundwater circulation, leading to the significant change of the amount and quality of groundwater, spatial and temporal distribution characteristics of groundwater. Meanwhile, a series of eco-environmental and geological problems like aquifer depletion, cone of depression, land subsidence, ground fissure, soil salinization, soil desertification and groundwater pollution have also been generated. To utilize groundwater resources reasonably, people propose the idea of sustainable development and utilization of groundwater (Sophocleous 2000; Kalf et al. 2005). Conti et al. (2016) assessed twelve key international groundwater governance texts using a normative framework of thirty principles categorized according to the dimensions of sustainable development. Farhadi et al. (2016) developed an agent-based-Nash modeling framework to find a sustainable solution for groundwater management in Daryan Aquifer, Fars Province, Iran, and optimal groundwater extractions are computed by NSGA-II optimization model. Mazi et al. (2016) presented a screening-level approach to the quantification of the key natural and human-determined controls and sustainability limits for the human use of coastal groundwater.

The eco-environmental and geological problems caused by the unreasonable development of groundwater can all be attributed to the functional degeneration and loss of groundwater. In 2003, scholars proposed the concept and evaluation technology method of groundwater function from the resources supply, maintenance of ecological system and stability of geological environment of groundwater. The evaluation of groundwater function is the foundation of the reasonable determination of sustainable yield of groundwater (Zhang et al 2008), which is also the extension and the latest achievements of the concept sustainable development of groundwater and the new hotspot in hydrogeology field. In 2006, China Geological Survey formally published Evaluation of Groundwater Function and Division Technical Requirement. Based on the natural attribute, social economic attribute and ecological environment attribute, Tang et al. (2012) established the divisional system of groundwater function in China starting from the dominant function of groundwater. Zhang et al. (2006, 2009) established the evaluation system of groundwater function and evaluated the groundwater function of Hutuo River basin. Du et al. (2013) took plain area in Henan Province as an example to build the evaluation index system of shallow groundwater function. Fan et al. (2009) evaluated the sustainability of regional groundwater based on the evaluation results of groundwater function in plain areas in Jilin Province. Sun et al. (2013) established the evaluation index system of groundwater function from the aspect of the supply and demand of groundwater and analyzed the groundwater function of the lower Liaohe River plain applying analytic hierarchy process and GIS spatial overlay analysis.

At present, the evaluation method, evaluation system and evaluation model of groundwater function are at the exploration stage and there exist two problems in the evaluation of groundwater function: the first is that the evaluation index system is complex and it is difficult to conduct data acquisition. The applicability of evaluation index system is poor; the second is that the results of groundwater function evaluation has a relative sense. When the research area is divided into several sub-regions, the strength of groundwater function of certain region is relative to the size of groundwater function in other regions in this research instead of relative to certain standard value, which is inconvenient to compare groundwater function among different regions.

Dissipative structure theory, coordination theory and mutation theory are called New Three Theories in system science. Prigogine established dissipative structure theory by combining non-equilibrium thermodynamics, non-equilibrium statistical physics and dynamics. The dissipative structure theory holds that a nonlinear open system far from equilibrium state exchanges material, energy and information with the outside world constantly. There exist nonlinear dynamic process and positive and negative feedback mechanism in the system. When the change of certain parameter in the system reaches a threshold, mutation, namely nonequilibrium phase transformation may occurs in the system, transforming from the original chaotic state to a new ordered dissipative structure in time, space or function. Therefore, dissipative structure theory can reveal the internal evolution mechanism of the system under certain external condition (Chang et al. 2002). The groundwater system satisfies the essential attribute of dissipative structure theory (Jiang et al. 2008). The groundwater system is a complex open system and there exist material flow, energy flow and information flow with the environment; groundwater system can maintain the order in time, space or function and the groundwater system is far from equilibrium state; the internal elements and sub-system of groundwater system are nonlinear structure; under the effect of certain external environment (natural or man-made), the groundwater system relies on its own structure and shows obvious self-organization characteristics. The self-organization process can be realized in certain external environment. The rise and fall of groundwater system leads to the system order. Therefore, groundwater system is dissipative structure and dissipative structure theory can be adopted to analyze the evolution of groundwater system function. This paper establishes a set of new and more adaptive evaluation model and functional classification standard of groundwater function by adopting order parameters of dissipative structure. This paper establishes the evaluation model and functional grading standard of groundwater function based on order degree and entropy and evaluates the groundwater function in Tianjin.

2. Materials and methods

2.1 Study area

Tianjin is located at 116°42′05″E~118°03′31″E, 38°33′57″N~40°14′05″N. Tianjin borders the Bohai Sea to the southeast, Yanshan Mountain to the north, Beijing and Hebei Province to the northwest. Tianjin is 172km from north to south and 104 km from east to west, as is shown in Figure 1. Tianjin is higher in the north and lower in the south, higher in the west and lower in the east. The terrain slow tilts from northwest to southwest, which is mountain proluvial and alluvial fan in order. The elevation is 50m to 10m. The elevation of alluvial plain and lacustrine plain connected to it is 2.5m to 10m. The southeast coastal area is marine depositional plain, and the majority is salt pans and low swampy land. The elevation is 1m to 2m. The annual mean precipitation is 567.7 mm and the precipitation distribution within the year is not uniform.70% to 75% precipitation concentrates in July to September. The annual mean amount of evaporation is 1092.2 mm and the aridity index is 1.9, belonging to semiarid region. The contradiction between supply and demand of water resources is obvious. Based on the characteristics of aquifer, we can classify aquifer into: fissure aquifer of clastic rocks, porous aquifer of loose rocks and karst-fissure aquifer of carbonate rocks. The vast plain area from mountain front to coast of the Bohai Sea is divided by Ninghe-Baodi fault. The south of fault zone is thick Cenozoic, whose occurrence is pore groundwater; the north of fault zone is the quaternary pore groundwater and the underlying bedrock pore groundwater. The bedrock’s depth is less than 300 m. The land subsidence is very serious in Tianjin due to unreasonable exploitation of groundwater.

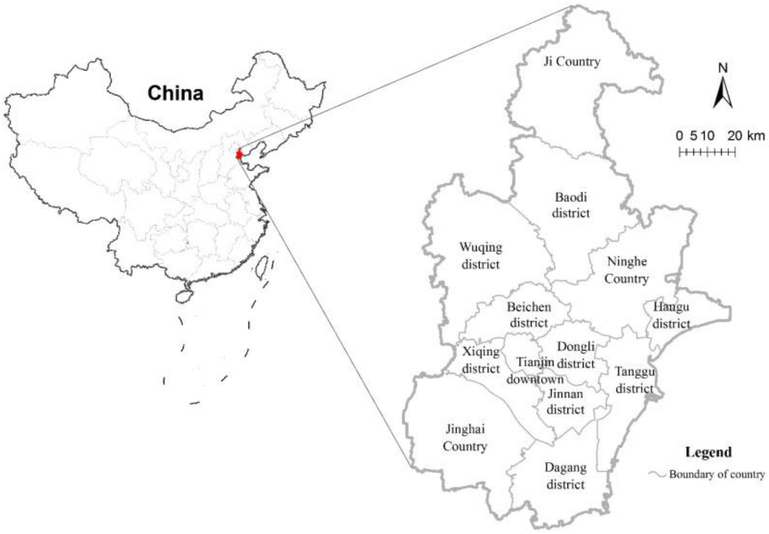


Fig 1 Location of Tianjin City

2.2 Orderliness of Groundwater System

Groundwater has multiple attribute functions including resources, ecology and geological environment. The groundwater system can be regarded as the organism of resources subsystem, ecology subsystem and geological environment subsystem, forming a complex relationship of mutually connected, mutually supported and mutually constrained. The groundwater system conforms to the systematic characteristics of dissipative structure, which is an ordered dissipative structure. The dissipative structure of groundwater system indicates that groundwater system is a dynamic ordered structure. The evolution process from low order degree to high order degree is the process of dissipative structure formation or transformation from one dissipative structure to another dissipative structure. However, the phase transformation results may not transform into a new order, but may transform into disorder. The order and disorder can transform into each other. The orderliness of groundwater system is that the resources, ecology and geological environment subsystems in the system can maintain a certain order and these subsystems are coordinated and moderate in combination. These subsystems can maintain dynamic equilibrium coordination, facilitating the stable development of geological environment subsystem and the balance of ecology subsystem. Finally, the virtuous circle and healthy evolution of groundwater system can be achieved.

2.3 Order parameter of groundwater function

Order parameters dominate the change of other parameters in dissipative structure and then dominate the whole evolution process of the system, whose value determines the order degree of the system. Therefore, the order degree and evolutionary direction of the system can be expressed in order parameters.

Groundwater has the function of resources, ecology and geological environment. Groundwater resources function (GRF) supply guarantee effect of groundwater resources with certain supply, storage and updating conditions. Therefore, the value of groundwater resources function can be expressed in modulus of groundwater resources, allowable withdrawal modulus of groundwater, change rate of groundwater level, rate of withdrawal and recharge of groundwater and withdrawal rate of groundwater resources. Groundwater ecology function (GEF) refers to the effect of groundwater system on the benign maintenance vegetation, lake, wetland and land quality. Therefore, the value of groundwater ecology function can be expressed in deviation value of ecology groundwater level, degree of mineralization of groundwater, soil salinity, soil moisture content and vegetation coverage. Groundwater geologic environment function (GGEF) refers to the supporting and protection effect of groundwater system on the occurrence of the geologic environment. Therefore, the value of groundwater geologic environment function can be expressed in rate of land subsidence, comprehensive index of groundwater quality, deviation value of geological stability control groundwater level and intrusion degree of seawater.

The order parameters and grading standard of groundwater function, based on main influencing factors of groundwater function, is shown in Table 1.

2.4 Order degree of Groundwater System

Groundwater system is dissipative structure and the phase transformation results may not transform into a new order, but may transform into disorder. For this, order degree is introduced in the evaluation of groundwater system function.

We set the groundwater subsystem as S_j and order parameters in the development process as $x_j=(x_{j1}, x_{j2}, \ldots, x_{jn})$, $n\geq1$. To calculate the order degree of order parameter x_{ji} in groundwater subsystem S_j, this paper adopts the concept of fuzzy mathematics and calculates the order degree of order parameters through fuzzy membership. That is to say, we need to calculate the membership of order parameter x_{ji} relative to each groundwater function level and then take the grade of each function grade as weight. After that, the order degree of order parameter is obtained. The lower semi-trapezoid distribution function is taken as the membership function.

Table 1 Grading standard of groundwater function order parameter

Type	Order parameter	Unit	Grading standard				
			Grade I	Grade II	Grade III	Grade IV	Grade V
			strong	moderately strong	moderate	moderately weak	weak
GRF	modulus of groundwater resources (B_1C_1)	$10^4m^3/a.km^2$	>35	25-35	15-25	5-15	<5
	allowable withdrawal modulus of groundwater (B_1C_2)	$10^4m^3/a.km^2$	>25	15-25	8-15	4-8	<4
	groundwater level change rate(B_1C_3)	m/a	<0.01	0.01-0.5	0.5-1.0	1.0-1.5	>1.5
	rate of withdrawal and recharge of groundwater (B_1C_4)	%	<10	10-30	30-60	60-90	>90
	withdrawal rate of groundwater resources (B_1C_5)	%	<30	30-80	80-100	100-120	>120
GEF	degree of mineralization of groundwater (B_2C_1)	g/L	<2	2-3.5	3.5-5.5	5.5-10	>10
	soil salinity (B_2C_2)	%	<0.55	0.55-0.73	0.73-0.87	0.87-1.35	>1.35
	vegetation coverage (B_2C_3)	%	>60	45-60	30-45	20-30	<20
	deviation value of ecology groundwater level(B_2C_4)	m	<0.2	0.2-0.5	0.5-1	1-1.5	>1.5
	soil moisture content(B_2C_5)	%	>6.27	4.17-6.27	3.14-4.17	1.57-3.14	<1.57
GGEF	rate of land subsidence (B_3C_1)	mm/a	<1	1-3	3-5	5-10	>10
	comprehensive index of groundwater quality (B_3C_2)		<0.8	0.8-2.50	2.5-4.25	4.25-7.2	>7.2
	deviation value of geological stability control groundwater level(B_3C_3)	%	<1	1-3	3-5	5-8	>8

intrusion degree of seawater (B_3C_4)	%	<2	2-10	10-20	20-30	>30

There are *m* order parameters in the *k*th groundwater subsystem S_k (k=1,2,3), the *i*th order parameter is x_{ki}. The standard value of the *j*th grade groundwater function of this order parameter is c_{ij} (i=1,2,…,m; j=1,2,…,n).

If x_{ki} is reverse index, then the membership γ of each function evaluation grade is:

$$\gamma_{i1}=\begin{cases}1 & x_{ki}\le c_{i1}\\ \dfrac{c_{i2}-x_{ki}}{c_{i2}-c_{i1}} & c_{i1}<x_{ki}\le c_{i2}\\ 0 & x_{ki}>c_{i2}\end{cases} \tag{1}$$

$$\gamma_{ij}=\begin{cases}1-\dfrac{c_{ij}-x_{ki}}{c_{ij}-c_{ij-1}} & c_{ij-1}\le x_{ki}\le c_{ij}\\ \dfrac{c_{ij+1}-x_{ki}}{c_{ij+1}-c_{ij}} & c_{ij}<x_{ki}\le c_{ij+1} \qquad j=2,\ldots,n-1\\ 0 & x_{ki}<c_{ij-1}, x_{ki}>c_{ij+1}\end{cases} \tag{2}$$

$$\gamma_{i1}=\begin{cases}1 & x_{ki}\le c_{i1}\\ \dfrac{c_{i2}-x_{ki}}{c_{i2}-c_{i1}} & c_{i1}<x_{ki}\le c_{i2}\\ 0 & x_{ki}>c_{i2}\end{cases} \tag{3}$$

If x_{ki} is forward index, then the membership γ of each function evaluation grade is:

$$\gamma_{i1}=\begin{cases}1 & x_{ki}\ge c_{i1}\\ \dfrac{x_{ki}-c_{i2}}{c_{i1}-c_{i2}} & c_{i2}\le x_{ki}<c_{i1}\\ 0 & x_{ki}<c_{i2}\end{cases} \tag{4}$$

$$\gamma_{ij}=\begin{cases}1-\dfrac{x_{ki}-c_{ij}}{c_{ij-1}-c_{ij}} & c_{ij-1}\ge x_{ki}\ge c_{ij}\\ \dfrac{x_{ki}-c_{ij+1}}{c_{ij}-c_{ij+1}} & c_{ij}>x_{ki}\ge c_{ij+1} \qquad j=2,\ldots,n-1\\ 0 & x_{ki}>c_{ij-1}, x_{ki}\le c_{ij+1}\end{cases} \tag{5}$$

$$\gamma_{in}=\begin{cases}0 & x_{ki}>c_{in-1}\\ 1-\dfrac{x_{ki}-c_{in}}{c_{in-1}-c_{in}} & c_{in-1}\ge x_{ki}\ge c_{in}\\ 1 & x_{ki}<c_{in}\end{cases} \tag{6}$$

The order degree $u_{ki}(x_{ki})$ of order parameter x_{ki} is:

$$u_{ki}\left(x_{ki}\right)=\gamma w=\sum_{j=1}^{n}\gamma_{ij}w_j \qquad i=1,2,\mathrm{L}\ ,m \tag{7}$$

In this equation, $u_{ki}(x_{ki})$ is the order degree of order parameter x_{ki}. w_j is the grade of each groundwater function grade. The order parameter is divided into 5 levels (Table 1), and thus w=[0.99 0.745 0.5 0.255 0.01].

$u_{ki}(x_{ki}) \in (0，1)$. The bigger the value of $U_k(x_k)$, the greater the contribution of order parameter x_{ki} to the order degree of subsystem S_k. The order degree $U_k(x_k)$ of all order parameters x_{ki} (i=1,2,…,m) in subsystem S_k to subsystem S_k is:

$$U_k(x_k)=\sum_{i=1}^{m}\varphi_i^k u_{ki}(x_{ki}), \qquad \varphi_i \geq 0, \qquad \sum_{i=1}^{m}\varphi_i^k=1 \tag{8}$$

In this equation, φ_i^k is the weight coefficient of order parameter x_{ki}, representing the role or position of subsystem S_k in the orderly operation of order parameter x_{ki}. We assume that every order parameter of the subsystem has the same weight, i.e., φ_i^k =1/m (k=1,2,3).

2.5 Grading standard of groundwater function

Because $u_{ki}(x_{ki}) \in (0，1)$ and the bigger the value of $U_k(x_k)$, the greater the contribution of order parameter x_{ki} to the order degree of subsystem S_k. The higher the order degree of subsystem, the stronger groundwater function; on the contrary, the lower the order degree of subsystem, the weaker groundwater function. Therefore, the order degree $U_k(x_k)$ of subsystem S_k can be adopted to represent the groundwater functional strength of subsystem.

$$F_k=U_k\left(x_k\right) \tag{9}$$

In this equation, F_k is the groundwater function of subsystem S_k. j=1, 2, 3 represent the subsystems of resources function, ecology function and geological environment function respectively.

Due to the limitation of groundwater system function within specific period, there are competition among order parameters in the subsystem. The order degree of subsystem cannot increase at the same time. The increase of order degree of one system may lead to the decrease of the order degree of other subsystems, making it impossible to determine the change of order degree of the system. The entropy theory of dissipative structure provides reference for us to settle this problem. Although we cannot adopt entropy to conduct quantitative calculation on the system evolution and it is difficult to express in explicit function using the entropy, yet we can conduct qualitative analysis on the system evolution direction by applying the relationship between entropy and order degree. That is to say, the order degree and the function of groundwater system will increase with the decrease of entropy. On the contrary, the order degree and the function of groundwater system will decrease with the increase of entropy.

Based on the definition of entropy, we can establish the entropy of order degree representing groundwater system function by adopting the order degree of order parameters. The function is:

$$F = -\sum_{k=1}^{3} \frac{1-F_k}{3} \log \frac{1-F_k}{3} \tag{10}$$

In this equation, F is total entropy of the whole groundwater system.

Based on the order degree and entropy of groundwater system function and considering $0<F_k<1$ and $0<F<0.5$, the grading standard of groundwater function is shown in Table 2.

Table 2 Grading standard of groundwater function

Grade	I	II	III	IV	V
Groundwater function	strong	moderately strong	moderate	moderately weak	weak
Groundwater resources function, F_1	≥0.8	0.6~0.8	0.4~0.6	0.2~0.4	<0.2
Groundwater ecology function, F_2	≥0.8	0.6~0.8	0.4~0.6	0.2~0.2	<0.2
Groundwater geologic environment function, F_3	≥0.8	0.6~0.8	0.4~0.6	0.2~0.2	<0.2
Groundwater function, F	≤0.24	0.24~0.35	0.35~0.42	0.42~0.46	>0.46

3. Results and Discussion

3.1 Order parameter of groundwater function in Tianjin City

Considering the characteristics of groundwater and data acquisition in the study area, the order parameters of groundwater resources function evaluation include modulus of groundwater resources, allowable withdrawal modulus of groundwater, change rate of groundwater level, rate of withdrawal and recharge of groundwater and withdrawal rate of groundwater resources. The order parameters of groundwater ecology function include degree of mineralization of groundwater, soil salinity and vegetation coverage. The order parameters of groundwater geological environment function include rate of land subsidence, comprehensive index of groundwater quality and deviation value of geological stability control groundwater level. The management of groundwater is conducted based on the administrative boundary, and thus the groundwater function evaluation of the study area is divided into 13 groundwater function evaluation areas based on administrative districts and counties. The order parameters of resources, ecology and geological environment function of groundwater are shown in Table 3, Table 4 and Table 5 respectively.

Table 3 Order parameter of groundwater resources function (GRF)

District	Order parameter				
	$B_1C_1/10^4m^3.km^{-2}$	$B_1C_2/10^4m^3.km^{-2}$	$B_1C_3/m.a^{-1}$	$B_1C_4/\%$	$B_1C_5/\%$
Baodi district	17.493	8.585	0.650	43.79	89.22
Beichen district	11.269	3.261	4.224	41.66	143.96
Dagang district	7.890	0.749	4.825	53.30	561.31
Dongli district	11.253	1.665	6.030	39.65	267.91
Hangu district	11.485	3.614	6.863	102.69	326.33
Ji Country	21.053	20.000	0.290	77.96	82.06
Jinan district	13.950	2.249	5.289	61.51	381.55
Jinghai Country	9.397	2.128	4.531	37.56	165.81
Ninghe Country	11.518	3.304	4.997	47.25	164.73
Tianjin downtown	7.941	3.213	4.162	55.09	136.18
Tanggu district	9.894	0.568	4.276	23.45	408.90
Wuqing district	12.670	6.558	3.945	56.37	108.91
Xiqingn district	11.343	3.882	7.954	60.54	176.90

Table 4 Order parameter of groundwater ecology function (GEF)

District	Order parameter		
	$B_2C_1/g.L^{-1}$	$B_2C_2/\%$	$B_2C_3/\%$
Baodi district	1.2	0.08	15.52
Beichen district	2.3	0.52	13.35
Dagang district	9	2.37	9.22
Dongli district	4	0.66	11.72
Hangu district	7	2.01	10.15
Ji Country	0.6	0.05	20.15
Jinan district	4	1.53	12.37
Jinghai Country	3.5	0.65	15.52
Ninghe Country	2.9	0.28	15.27
Tianjin downtown	3	0.48	8.34
Tanggu district	8	2.43	7.03
Wuqing district	1.5	0.25	15.96
Xiqingn district	3.2	0.63	11.34

Table 5 Order parameter of groundwater geologic environment function (GGEF)

District	Order parameter		
	$B_3C_1/mm.a^{-1}$	B_3C_2	$B_3C_3/\%$
Baodi district	3.62	5.22	3.40
Beichen district	22.46	6.05	8.45
Dagang district	32.25	7.17	10.22
Dongli district	25.00	6.18	9.45

Hangu district	37.68	5.02	12.34
Ji Country	0.00	4.15	0.00
Jinan district	44.57	6.69	14.33
Jinghai Country	14.13	7.07	7.38
Ninghe Country	17.03	4.02	7.88
Tianjin downtown	15.58	6.27	7.76
Tanggu district	21.38	6.12	8.25
Wuqing district	34.06	5.34	10.65
Xiqingn district	47.83	6.33	14.54

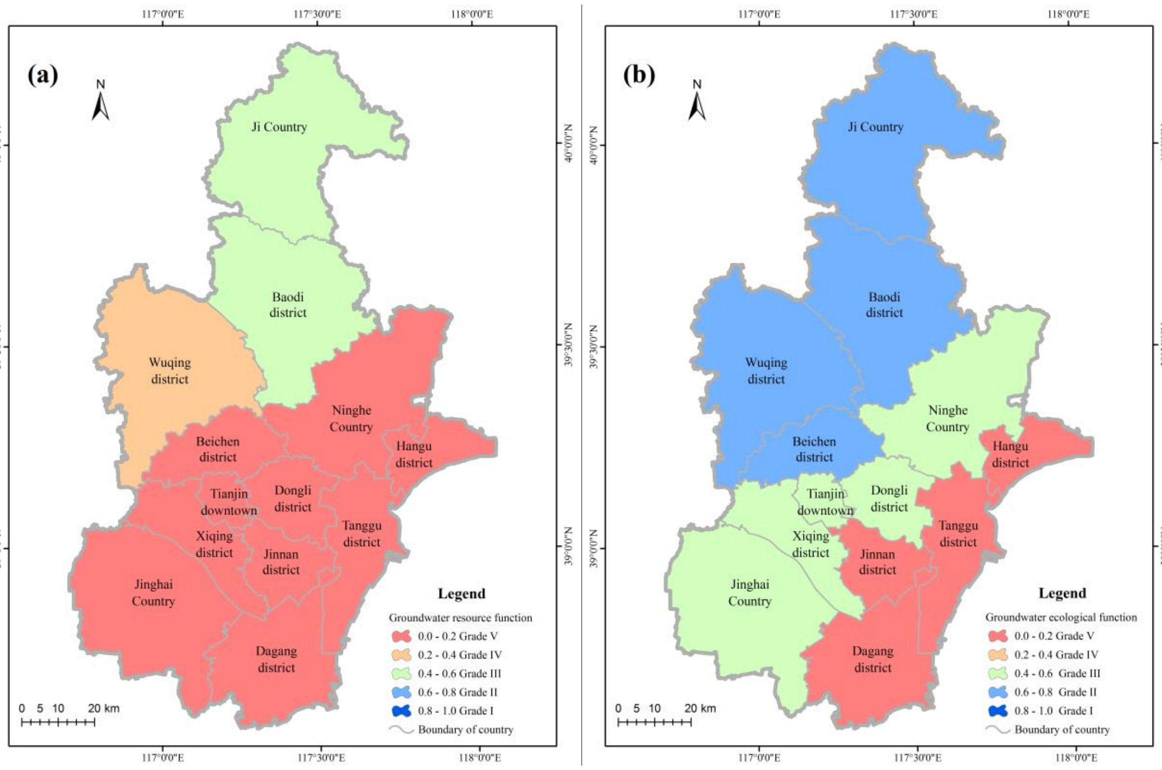
3.2 Groundwater function in Tianjin City

According to order parameters and grading standard of groundwater in the study area and the groundwater function evaluation method based on the dissipative structure, we can obtain the resources, ecology and geological environment function of groundwater in Tianjin. The groundwater function grade of different regions is obtained based on the grading standard of groundwater function evaluation. The evaluation results are shown in Table 6 and Figure 2.

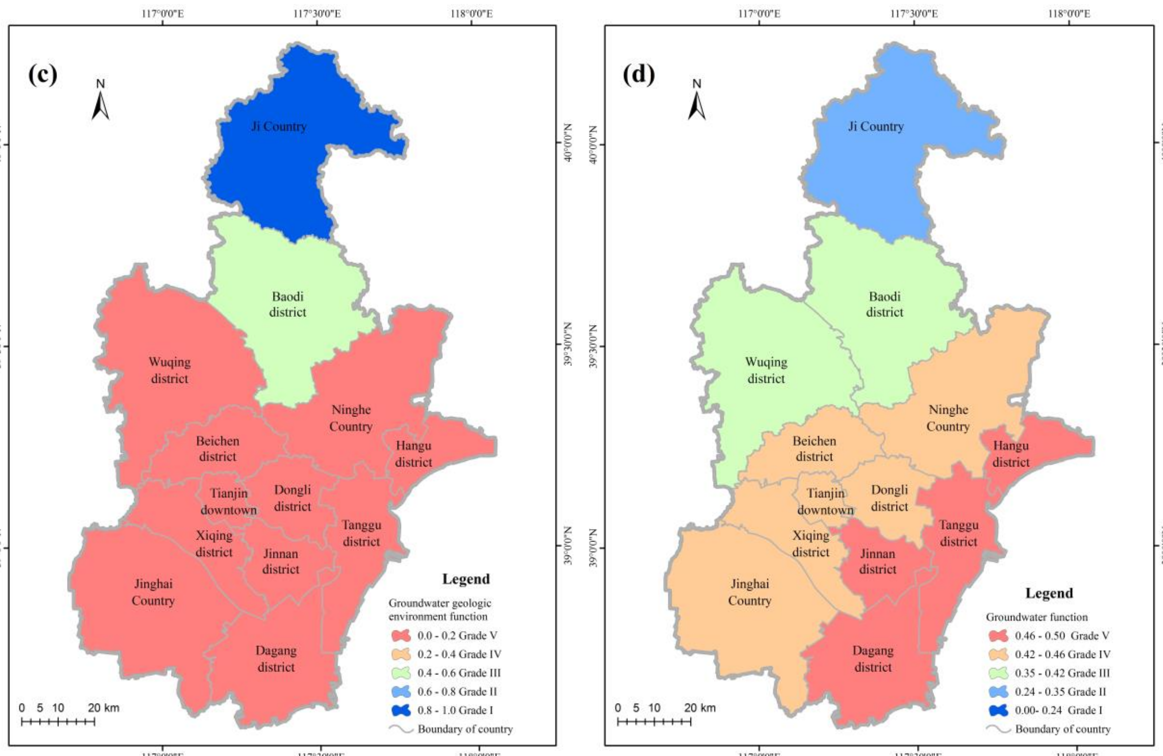
The resources function index of groundwater in Tianjin is 0.066 ~ 0.552, indicating that the overall resources function of groundwater is weak. The resources function of groundwater in Ji Country and Baodi District is moderate, i.e. Grade III, that in Wuqing District is moderately weak, i.e. Grade IV, and those in other areas are weak, i.e. Grade V. Comparatively, the resources function of groundwater in Ji County is the strongest and that in Hangu District is the weakest. The groundwater ecological function index in Tianjin is between 0.046 ~ 0.666. The ecology functions of groundwater in Ji County, Baodi District, Beichen District and Wuqing District are moderately strong, i.e. Grade II, those in Dongli District, Jinghai County, Ninghe County, Tianjin downtown and Xiqing District are moderate, i.e. Grade III and those in Jinnan District, Dagang District, Hangu District and Tanggu District are weak, i.e. Grade V. Comparatively, the ecology function of groundwater in Ji County is the strongest, while that in Dagang District is the weakest. The geological environment function index of groundwater in Tianjin is between 0.012 ~ 0.8. The geological environment function of groundwater in Ji County is strong, i.e. Grade I, while that in Baodi District is moderate, i.e. Grade III, and those in other areas are weak, i.e. Grade V. Comparatively, the geological environment function of groundwater in Ji County is the strongest, and that in Dagang District is the weakest. The comprehensive function index of groundwater in Tianjin is between 0.308 ~ 0.473. Comparatively, the comprehensive function of groundwater is the strongest in Ji County and the weakest in Dagang District. The comprehensive function of groundwater in Ji County is moderately strong, i.e. Grade II, and those in Baodi District and Wuqing District are moderate, i.e. Grade III. Ji County, Baodi District and Wuqing District is located in the alluvial-proluvial fan of the Jiyun River and the Chaobai River. The aquifer in this area contains coarse grains, and each sand layer is thick, with strong vertical continuity and good water permeability, providing favorable conditions for infiltration supplement and water storage. Besides, due to the good groundwater quality and the strong water supply capacity, this area is a groundwater resources supply area. The comprehensive functions of groundwater in Beichen District, Dongli District, Jinghai County, Ninghe County, Tianjin downtown and Xiqing District are moderately weak, i.e. Grade IV. The functions of groundwater are in disharmony, and the ecology function or ecological environment function of groundwater has encountered problems. In these places, groundwater abstraction should be moderately controlled. The comprehensive functions of groundwater in Dagang District, Hangu District, Jinnan District and Tanggu District are weak, i.e. Grade V. Groundwater function is in serious conflict and the ecology function or ecological environment function of groundwater has encountered serious problems. In these places, groundwater abstraction should be strictly controlled.

Table 6 Groundwater function of Tianjin City

District	GRF		GEF		GGEF		Groundwater function	
	F_1	Grade	F_2	Grade	F_3	Grade	F	Grade
Baodi district	0.475	III	0.663	II	0.476	III	0.371	III
Beichen district	0.170	V	0.631	II	0.074	V	0.424	IV
Dagang district	0.123	V	0.046	V	0.012	V	0.473	V
Dongli district	0.174	V	0.431	III	0.066	V	0.449	IV
Hangu district	0.066	V	0.111	V	0.116	V	0.471	V
Ji Country	0.552	III	0.666	II	0.800	I	0.308	II
Jinan district	0.149	V	0.197	V	0.038	V	0.467	V
Jinghai Country	0.166	V	0.460	III	0.051	V	0.447	IV
Ninghe Country	0.161	V	0.575	III	0.157	V	0.430	IV
Tianjin downtown	0.120	V	0.570	III	0.075	V	0.435	IV
Tanggu district	0.198	V	0.083	V	0.070	V	0.468	V
Wuqing district	0.257	IV	0.663	II	0.105	V	0.413	III
Xiqingn district	0.138	V	0.488	III	0.058	V	0.445	IV



(a) Groundwater resources function, GRF (b) Groundwater ecology function, GEF



(c) Groundwater geologic environment function, GGEF (d) Groundwater function

Fig. 2 Groundwater function of Tianjin City

4. Conclusion

Groundwater system is dissipative structure system and has resources function, ecology function and geological environment function. This paper establishes the order parameters and grading standard representing resources, ecology and geological environment function of groundwater based on dissipative structure theory and main influencing factors of groundwater function. By adopting the idea of fuzzy mathematics, this paper calculates the order degree of order parameters based on fuzzy membership and represents the strength of groundwater function based on the order degree of resources subsystem, ecology subsystem and geological environment subsystem of groundwater. By adopting the order degree of subsystems, this paper represents the groundwater system comprehensive function based on entropy. Based on the grading standard of groundwater function evaluation, this paper obtains the groundwater function and function grade of different areas in Tianjin. The results indicate that the comprehensive function of groundwater in Ji County is moderately strong; the comprehensive function of groundwater in Baodi District and Wuqing District is moderate. The water source supply capacity in Ji County, Baodi District and Wuqing District is good, which are groundwater supply areas. The comprehensive function in Wuchen District, Dongli District, Jinghai County, Ninghe County, Tianjin downtown and Xiqing District is moderately weak, which means that the exploitation of groundwater should be moderately controlled. The comprehensive function in Dagang District, Hangu District, Jinnan District and Tanggu District is weak, which means that the exploitation of groundwater should be strictly controlled.

The function evaluation of groundwater is the new hotspot in in hydrogeology field and the evaluation methods and evaluation systems are still in the exploratory stage. This paper adopts dissipative theory to evaluate groundwater function and the selection of order parameters of groundwater function is based on the groundwater function in Tianjin. The selection of order parameters of groundwater function in other areas should be based on local characteristics and functional screening of groundwater system. In addition, this paper adopts equal weight for the weight coefficient of the effect of order degree in the subsystem representing order parameters and subjective weighting method and objective weighting method like Delphi, AHP (analytic hierarchy process) and rough set can be adopted in follow-up studies.

The groundwater management in China is mainly based on allowable withdrawal groundwater. At present, management model of allowable withdrawal groundwater and key groundwater level is going to be implemented. Groundwater function evaluation is an important basis for the determination of allowable withdrawal groundwater. Therefore, the coupling of groundwater function evaluation model can be taken into consideration in the design of groundwater management model to establish groundwater management model based on groundwater function.

Acknowledgments

The study was financially supported by Non-Profit Industry Specific Research Projects of Ministry of Water Resources, China, Grant NO: 201401041, Science and Technology Research Key Project of the Education Department of Henan Province, Grant NO: 14A170006, and Open Research Fund of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (China Institute of Water Resources and Hydropower Research), Grant NO: IWHR-SKL-201208.

References

1. M. Sophocleous, From safe yield to sustainable development of water resources-the Kansas experience, 2000, Journal of Hyrology, vol. 235, pp. 27-43.
2. F. R. P. Kalf, D. R. Woolley, Applicability and methodology of determining sustainable yield in groundwater systems, 2005, Hydrogeology Journal, vol. 13, no. 2, pp. 295-312.
3. K. I. Conti, J. Gupta, Global governance principles for the sustainable development of groundwater resources, 2016, International Environmental Agreements-Politics Law and Economics, vol. 16, no. 6, pp. 849-871.
4. S. Farhadi, M. R. Nikoo, G. R. Rakhshandehroo, M. Akhbari, M. R. Alizadeh, An agent-based-nash modeling framework for sustainable groundwater management: A case study, 2016, Agricultural Water Management, vol. 177: pp. 348–358.
5. K. Mazi, A. D. Koussis, G. Destouni, Quantifying a sustainable management space for human use of coastal groundwater under multiple change pressures, 2016, Water Resources Management, vol. 30, no. 12, pp. 4063-4080.
6. G. H. Zhang, M. J. Yan, L. Z. Yang, Z. P. Liu, Relationship between the groundwater sustainable yield and groundwater function assessments, 2008, Geological Bulletin of China, vol. 27, no. 6, pp. 875-881.
7. K. W. Tang, Y. Tang, Y. Y. Li, J. Hou, Technical system of functional division for groundwater and its application in China, 2012, Shuili Xuebao, vol. 43, no. 11, pp. 1349-1356.

8. G. H. Zhang, J. M. Shen, Z. L. Nie, J. Z. Wang, M. J. Yan, M. L. Hao, Theory and methodology of regional groundwater function and sustainable utilization assessment in China, 2006, Hydrogeology & Engineering Geology, no. 4, pp. 62-66.
9. G. H. Zhang, L. Z. YANG, Z. L. NIE, J. M. Shen, J. Z. Wang, M. J. Yan, Assessment of groundwater function in north China plain, 2009, Resources Science, vol. 31, no. 3, pp. 368-374.
10. J. L. Du, M. G. Jin, Y. C. Luo, X. Q. Wei, Assessment index system for shallow groundwater function: A case study on the plain and hummock of Henan Province, 2007, Water Resources Protection, vol. 23, no. 6, pp. 89-92.
11. W. Fan, C. L. Xiao, Q. H. Xiong, X. J. Liang, Study on sustainability assessment of groundwater function in plain area of Jilin Province, 2009, Water Resources Protection, vol. 25, no. 3, pp. 14-17.
12. C. Z. Sun, X. M. Li, Groundwater function assessment based on ArcGIS in the lower reach of the Liaohe river plain, 2013, Scientia Geographica Sinica, vol. 33, no. 2, pp. 175-180.
13. J. X. Chang, Q. Huang, Y. M. Wang, X. J. Xue, Water resources evolution direction distinguishing model based on dissipative structure theory and gray relational entropy, 2002, Shuili Xuebao, vol. 11: pp. 107-112.
14. J. Y. Jiang, J. F. Cao, S. Li, B. Wang, Analysis on the evolution of groundwater system using the theory of dissipative structure, 2008, Research of Soil and Water Conservation, vol. 15, no. 1, pp. 122-124.